Technical Document 2608
October 1993

The High-Frequency Benchmark Propagation Program

J. A. Ferguson
C. H. Shellman

Approved for public release; distribution is unlimited.

Best
Available
Copy

Technical Document 2608
October 1993

The High-Frequency Benchmark Propagation Program

J. A. Ferguson
C. H. Shellman

NAVAL COMMAND, CONTROL AND OCEAN SURVEILLANCE CENTER RDT&E DIVISION
San Diego, California 92152-5001

K. E. EVANS, CAPT, USN
Commanding Officer

R. T. SHEARER
Executive Director

ADMINISTRATIVE INFORMATION

Work for this report was performed by members of the Ionospheric Branch, Code 541, in the Ocean and Atmospheric Sciences Division of the Naval Command, Control and Ocean Surveillance Center, RDT&E Division, San Diego, California.

Released by
J. A. Ferguson, Head
Ionospheric Branch

Under authority of
J. H. Richter, Head
Ocean and Atmospheric
Sciences Division

RV

CONTENTS

FIGURES

INTRODUCTION

The goal of this work is the development of techniques that permit timely and efficient evaluation of different propagation models. The resulting program is to be as sophisticated as possible with concerns for computer run time to be subordinate to the use of realistic models of the environment. Employed with new databases of high-latitude propagation measurements, this model will be used to evaluate and improve the faster-running models and point to deficiencies in the ionospheric models and the high-frequency (HF) prediction models. In addition, the development of new graphical displays will enhance understanding of the propagation environment. The emphasis of this development is on the personal computer for portability and ease of access. The current operating system is OS/2, Version 2.1. One of the modes of graphical output is specific to this operating system.

SPATIAL SMOOTHING

The first step in the development of the HF Benchmark is the development of a generalized spatial smoothing routine that will accept arbitrary ionospheric profiles. A candidate spatial smoothing algorithm was developed by Paul [1991, 1993] who demonstrated, with satisfying results, a general function that permitted fitting a set of irregularly spaced discrete data. Ferguson and Shellman [1991] and Ferguson [1993] applied this algorithm to a three-dimensional array of ionospheric profiles of electron density with altitude distributed in a regular grid of latitude and longitude. The fundamental problem with this technique, when applied to large data sets, is the large amount of time required to obtain a set of interpolation coefficients. This limits the flexibility of the resulting program because even small changes in the propagation path require repetition of the whole iterative process. We now have a new, more flexible, and faster running technique employing a three-dimensional cubic spline interpolation.

The new procedure is quite straightforward. The basic input to the program requires definition of a reference path, usually between a transmitter and receiver. The program automatically sets up a uniform grid of locations relative to this reference path. These locations are uniformly spaced along the reference path and along great circles perpendicular to it. The current configuration is for points along the path to be 200 km apart and for the points perpendicular to the path to be at ± 400 and ± 200 km from it. The electron densities are computed at regular intervals of 10 km in height. Following standard practice, it is actually the logarithm of the electron densities that is interpolated.

Let us designate the matrix of ionospheric parameters as $f(i,j,k)$, where i, j, and k represent values along the path, perpendicular to the path, and in height, respectively. Since the number of points along the path is usually much greater than the number of points perpendicular to the path or the number of heights, coefficients for the cubic spline interpolation along the reference path (parametric in j and k) are computed and stored only one time for each run. At an arbitrary point (x,y,z), we use these coefficients to compute at set of interpolated values, $f_x(j,k)$, representing the original function in the y-z plane at x. Then, by using these $f_x(j,k)$ values, we compute a set of coefficients for cubic spline interpolation (parametric in k) along each of the short paths perpendicular to the reference path. These coefficients are used to interpolate a set of interpolated values, $f_{xy}(k)$, representing the function along the z axis at (x,y). Finally, we use the $f_{xy}(k)$ along the z axis to compute a set of coefficients for the cubic spline interpolation along the z axis, which in turn, are used to get an interpolated value, f_{xyz} at the desired point. Since we are using cubic spline interpolation, we also get continuous derivatives in all three directions (necessary for the ray tracing). We achieve a lot of computational efficiency in solving for the coefficients because the set of equations which must be solved are tri-diagonal, and the coefficients of the set of simultaneous equations to be solved for each set of spline coefficients are the same in all three spatial directions.

Four subroutines are used to implement the interpolation. The routine named *GRD_Model* takes the parameters of the reference path and sets up the matrix of ionospheric data. This routine also sets up the interpolation and calls the interpolation routine. The routine named *GRD_Coeff* does the cubic spline interpolation for the ionospheric density and its derivatives. The routine *XYThPh* does coordinate conversion between geographic coordinates and the quasi-Cartesian coordinate system used in the interpolation routine. This routine also calculates the partial derivatives of geographic coordinates with respect to the quasi-Cartesian coordinates. The routine named *PGeoPMag* computes partial derivatives of geographic coordinates with respect to geomagnetic coordinates.

IONOSPHERIC MODEL

The ionospheric model used in the program has been updated to the Parameterized Ionospheric Model (PIM), Version 1.05. (PIM is available from Computational Physics Inc., 385 Elliot St., Newton, MA 02164.) The realtime version of this program is described by Daniels [1991]. A driver routine, named *Get_Profile*, has been developed for this model. It uses solar parameters such as 10.7 cm flux and sunspot number, supplied by the user, to prepare inputs for the PIM. These user inputs are described later in this report. The driver routine replaces a number of routines supplied as part of the PIM. No changes other than those required for the current operating system have been made to the subroutines of the PIM to allow quick replacement or update of the ionospheric model in the future.

The PIM has a few known shortcomings. These include a discontinuity in the E-layer at the boundary between middle and high latitudes. There can be unusually steep density gradients and bumps in the top and bottom sides of the ionospheric profile. These problems are being addressed by the developers of the model.

RAY TRACING

As in Ferguson and Shellman [1991] and Ferguson [1993], the HF Benchmark continues to use the Jones and Stephenson [1975] ray tracing model. This is a versatile program with full allowance for externally specified models of the electron density, collision frequency, and geomagnetic field. Every effort has been made to retain this flexibility in its implementation in the HF Benchmark. In particular, the input requirements are nearly identical to the original Jones and Stephenson version with the spatial smoothing algorithm being specified as an ionospheric model named GRDMODEL. When the program sees GRDMODEL as the ionospheric model, the next input record is read as a case identification consisting of one word, call this word the *CASE-ID*, which forms the root of the file name for all subsequent outputs. For example, the parameters of the ray paths are stored in a file with a name of the form *CASE-ID.RAY* and the execution log is written to a file names *CASE-ID.LOG*. During execution of the program, a summary of progress is written to the screen, but all of the detailed output is written to this log file. In the present implementation of the HF Benchmark program, the calculations of the spatial derivatives of the ionospheric electron densities require that the magnetic field model used in the ray tracing be that of a dipole ("DIPOLY" in the Jones and Stephenson input specification).

In addition to the original program inputs, a number of additional parameters, summarized in figure 1, have been introduced. The change to the new interpolation algorithm results in removing a number of parameters previously added by Ferguson and Shellman [1991]. The value of parameter 100 indicates whether to compute the ionospheric profiles (a value of 1) or to use an existing file of ionospheric profiles (a value of 9). If the value of parameter 100 is 1, then the program computes the required matrix of ionospheric profiles and writes them to a file named *CASE-ID.GRD*. The meanings of parameters 111 through 116 are self evident. Parameter 117 is a flag to indicate the direction of the solar magnetic field, B_y. Parameters 118 and 119 set lower and upper limits, respectively, on the heights of the ionosphere. If the value of parameter 100 is 9, the values of the parameters 118 and 119 may be different from those used to compute the ionospheric profiles found in the file. This allows the user to experiment with implicit removal of E layer effects or to lower the effective top of the ionosphere.

Parameters 130, 131 and 132 set up the parameters of the ionospheric display for the reference path. The first parameter 130 simply initiates the block of input. Parameter 131 defines the quantity to be plotted. Two views of this quantity are produced: the first view is in a vertical plane passing through the endpoints of the reference path; the second is in the horizontal plane at a height defined by parameter 132. The original intention was to have the HF Benchmark program generate this display, but it is much easier to have a separate program, named GridPlot, do this for now.

Because the ionosphere is defined over a limited area, the ray tracing routines have been modified to test for the ray path moving outside of the defined area. An appropriate message is printed into the log file when this occurs. Occasionally, if the index of refraction becomes negative and the problem cannot be circumvented, we terminate the calculations for the current ray and print an appropriate message into the log file. A number of other minor procedural modifications have been made to the ray tracing program to facilitate running it on a PC.

```
100    1.         Electron profile file specification: 1.=calculate; 9.=read)
110               Input for Parameterized Ionospheric Model
111    1.           number of the month
112   31.           day of the month
113 1991.           year
114 1200.           UT in hhmm format
115  100.           10 cm flux
116    1.           kp
117    1.           index for sign of By: =1 for '+'; =-1 for '-'
118  160.           ht minimum
119  600.           ht maximum
130               Plot of ionospheric parameters
131                 =0. no output
131                 =1. LOG10(Ne)
131                 =2. plasma frequency
131    1.           =3. X=1, X+Y=1, X-Y=1
132  350.           height at which to do horizontal contours
```

Figure 1. Parameters added to the ray trace input array to support the HF Benchmark.

SAMPLE PROBLEM

A sample program is presented here to illustrate the unification of the individual models. The input parameters for the program are shown in figure 2. The path is defined in geographic coordinates from 68.5°N, 32.5°E *to* 55.5°N, 117.1°W (*parameters* 4, 5, 19, and 20). The computed geographic bearing angle from the transmitter to the receiver is 339.3° and the path length is 6000 km; therefore, the initial azimuth of the rays is set to 340° clockwise from North (parameter 11). Ordinary rays will be launched at this azimuth at elevation angles from 0° to 15° (parameters 15 and 16) in steps of 3° (parameter 17). The ionospheric profiles are generated for 15 December 1991 at 1500 UT (parameters 11 through 114). The 10 cm flux is 70, the k_p is 2, and the direction of the sun's magnetic field, B_y, is positive (parameters 115 through 117). Electron densities are computed from 90 to 400 km (parameters 118 and 119). If so requested, plots of the ionospheric parameters will give plasma frequency in the vertical plane and in a horizontal plane at 200 km (parameters 131 and 132). Plots of the iononspheric parameter and of the ray paths will be made in the plane of the reference path (parameters 82 through 85) and the horizontal displays will have an extent of 300 km (parameter 87).

Contour plots of the plasma frequency in the vertical plane along the path are shown in the top panel of figure 3, and contours of the plasma frequency in the horizontal plane at an altitude of 200 km are shown in the bottom panel. This display is generated by an auxiliary program named GridPlot. This program uses the same input as the HF Benchmark and calculates the selected ionospheric parameter by using the file containing the ionospheric profiles. It is clear that the ionosphere is changing in all three dimensions. A new feature of the graphical output is the use of filled contour plots instead of the contour lines used in the past. In this gray shade version, there is not enough resolution to visualize the complexity of the ionospheric variation; however, this complexity is evident when the displays are viewed in color.

```
gridmodel            Ionospheric model name
sample               Coefficients file name; GRD extension
                     Ionospheric perturbation name (none)
dipoly               Geomagnetic field model name
expz                 Collision frequency model name
Sample problem
  1                  Ray type
  1                    =  1. ordinary ray
  1                    =  0. no field case
  1    -1.             = -1. extraordinary ray
  7     4.           Initial frequency, MHz
  8     4.             final frequency
  9     2.             step in frequency
 11   340.       deg Initial azimuth angle, degs clockwise from north
 12   340.       deg   final azimuth angle
 13    10.       deg   step in azimuth angle
 15     0.       deg Initial elevation angle, deg
 16    15.       deg   final elevation angle
 17     3.       deg   step in elevation angle
  3     0.           Transmitter height, km
  4    68.5      deg   transmitter latitude, deg north
  5    32.5      deg   transmitter longitude, deg east
 18     0.           Receiver height above the earth, km
 19    55.5      deg   receiver latitude, deg
 20  -117.1      deg   receiver longitude, deg
 22    21.           Number of hops
 28                  Debug printout
 28                    =1 basic diagnostic printout
 28     0.             =2 also print r,drdt,hamiltonian and ionospheric terms
 81     0.           Plot flag
 82    68.5      deg   left  latitude  of plot, deg north
 83    32.5      deg   left  longitude of plot, deg east
 84    55.5      deg   right latitude  of plot, deg north
 85  -117.1      deg   right longitude of plot, deg east
 87   300.             horizontal projection ymax, km
 90     0.             plt_device: 0.=os2; 1.=pj1; 2.=lj3; 3.=file
100     1.           Electron profile file specification: 1.=calculate; 9.=read
110                  Input for ionospheric model
111    12.             number of the month
112    15.             day of the month
113  1991.             year
114  1500.             UT in hhmm format
115    70.             10 cm flux
116     2.             kp
117     1.             index for sign of By: =1 for '+'; =-1 for '-'
118    90.             ht minimum
119   400.             ht maximum
130                  Plot of ionospheric parameters
130                    =0. no output
130                    =1. LOG10(Ne)
130                    =2. plasma frequency
131     1.             =1. LOG10(Ne)
132   200.             height for horizontal contours
                     A blank in columns 1-3 ends the current input
STOP                 End of run
```

Figure 2. Inputs for sample problem.

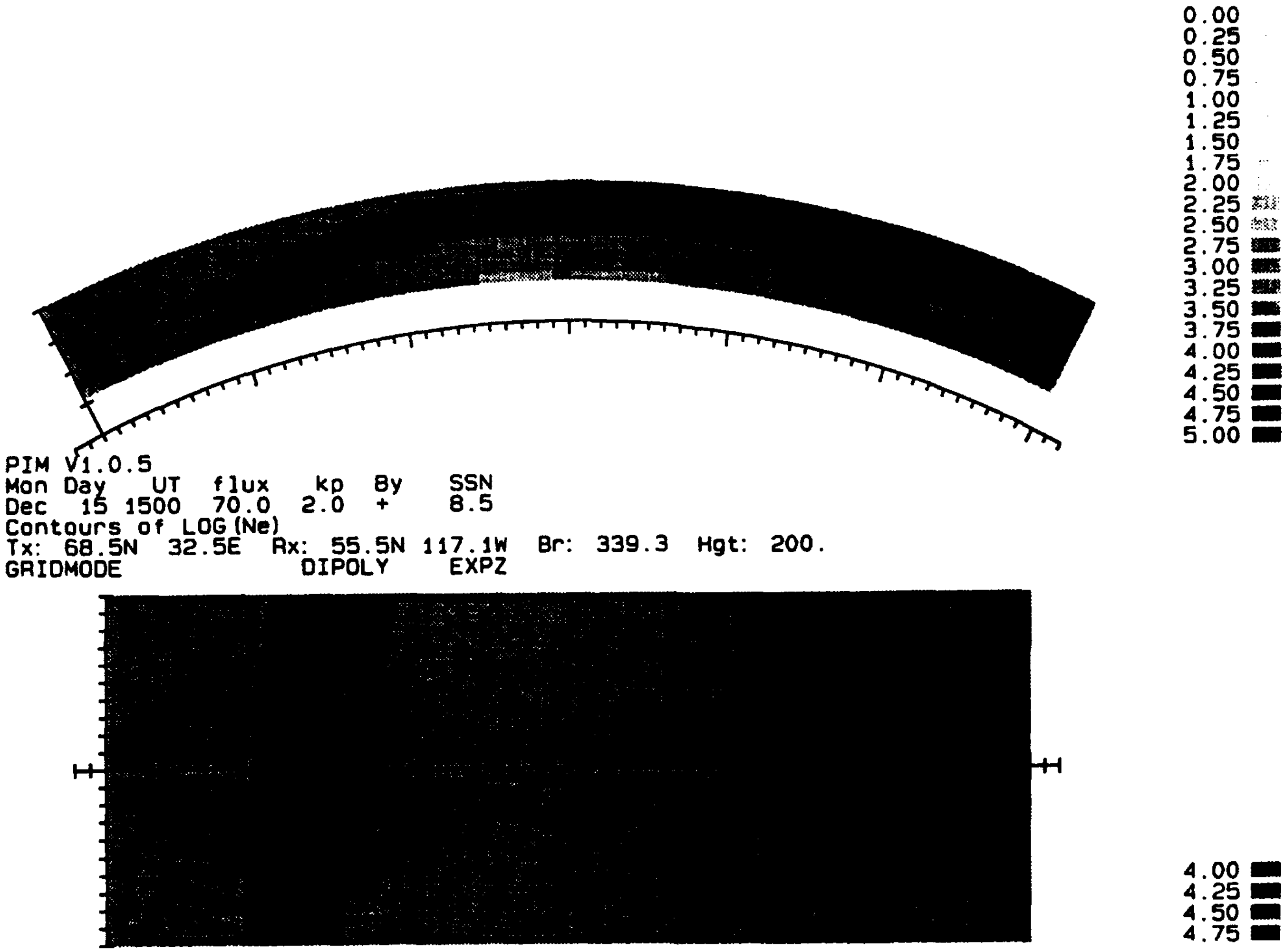

Figure 3. Plots of contours of constant values of the logarithm of the plasma frequency in the vertical plane along the great circle path passing through the transmitter and receiver in the horizontal plane at 200 km.

Ray paths for the extraordinary ray at 4 MHz are shown in figure 4. The top panel shows the projection of the ray paths onto the vertical plane passing through the transmitter and the receiver. The bottom panel of figure 4 shows the projection of the ray paths onto the ground with locations above the horizontal axis being to the west of the propagation path. We see that the off-path variation of the ionosphere causes some deflection of the ray paths.

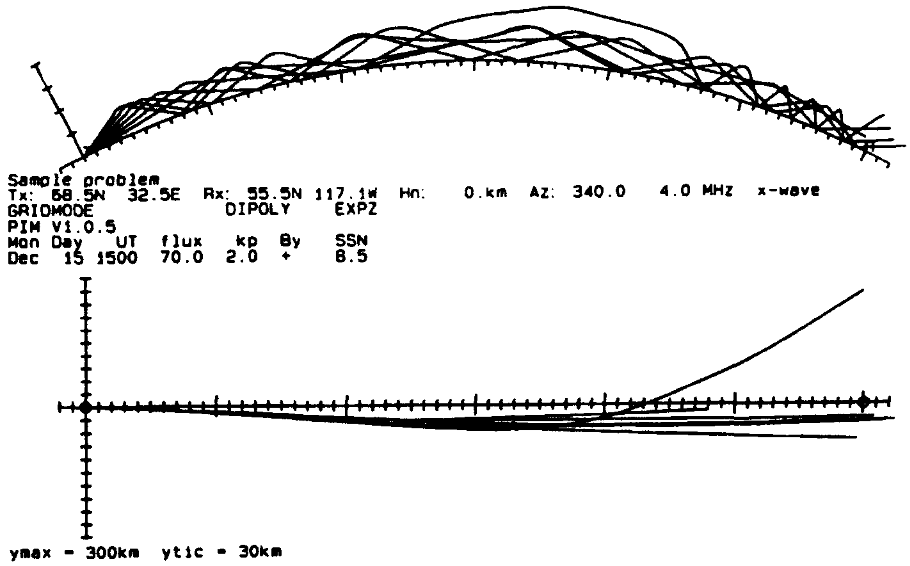

Figure 4. Plots of the ray paths for the extraordinary ray at 4 MHz in the vertical plane passing through the transmitter and the receiver (top panel) and in the horizontal plane (bottom panel).

One of the displays is a global view showing contours of the ionospheric profile in a fixed meridian, and the other is a view along short paths (a subset of the global view). In each display, contours of the electron density taken directly from the ionospheric model are shown. An example of the global display is shown in figure 6. The map projection is orthographic with the observation point in the center of the display. The location of this point is specified by the user. Superimposed on the circle representing the earth are a series of lines indicating land masses. There are a series of lines, ranging from solid, through dashes of various lengths, to dotted. These lines indicate the position of solar zenith angles, ranging from 90 degrees (solid) to 99 degrees (dotted), to show where the day-night transition is located. If it is visible from the observation side of the globe, the sub-solar point is also shown. The vertical scale for points above the earth's surface is specified by the user setting the number of inches between the earth's surface and the top of the model ionosphere. The auroral bulges are visible and the differences between the daytime and nighttime ionospheres are evident. The data set required to make this display is generated by a program named Globe, and the plots are generated by a program named GlobePlot.

The second display is a modification of the first, a sample of which is shown in figure 7. The primary difference from the global display is the shorter path length which allows scaling of the vertical dimension closer to the horizontal dimension. Consistent with the names used above, the data set required to make this display is generated by a program named Cntr, and the plots are generated by a program named CntrPlot. This display is similar to the one generated by the HF Benchmark program, lacking the horizontal display; furthermore, the Benchmark display is the result of the spline interpolation used in the ray tracing, while the display shown in figure 7 is the result of computing ionospheric profiles closely spaced in distance.

FUTURE PLANS

Our primary goal in the next year is to exercise the program over propagation paths we have measured so that we can make comparisons. We can then begin to sort out what is important in the ionospheric model and what is not relative to HF propagation. There are known shortcomings in the ionospheric model, but we must wait for its developers to solve them. A minor problem in the ray tracing must be fixed, namely, the ray path is often extrapolated during the calculation. Sometimes this extrapolation puts a calculation point outside of the defined ionosphere and we get a negative index of refraction. Currently, we simply stop tracing that particular ray and continue with the next one. We have to expand the checks on the ray being out of bounds to solve this problem. The current problem is quite simple to use and the computational throughput is acceptable for small scale studies of HF propagation.

REFERENCES

Daniels, R. W. 1991. "Parameterized Real-Time Ionospheric Specification Model." PRISM Version 1.0, Phillips Laboratory TR 91–2299 (Dec).

Ferguson, J. A. 1993. "Improvements to the High-Frequency Benchmark Propagation Analyais Program." NRaD TD 2411 (Jan).

Ferguson, J. A., and C. H. Shellman. 1991. "Spatial Smoothing of Ionospheric Parameters for Use in the High-Frequency Benchmark Propagation Analysis Program." NOSC TR 1469 (Nov).

Jones, R. M., and J. J. Stephenson. 1975. "A Versatile Three-Dimensional Ray Tracing Computer Program for Radio Waves in the Ionosphere." U.S. Department of Commerce Office of Telecommunications Report 75–76 (Oct).

Paul, A. K. 1991. "Fitting of Discrete Irregularly Spaced Discrete Data with Differentiable Functions: Application to Ray Tracing in the Ionosphere." NOSC TR 1405 (Mar).

Paul, A. K. 1993. "Generation of Electron Density Models with Continuous Gradients From Discrete Data." *Adv. Space Res.*, vol. 13, pp. 33–38.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	October 1993	Final: Oct 1993

4. TITLE AND SUBTITLE

THE HIGH-FREQUENCY BENCHMARK PROPAGATION PROGRAM

5. FUNDING NUMBERS

AC: DN302214
PE: 0602435N

6. AUTHOR(S)

J. A. Ferguson, C. H. Shellman

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Naval Command, Control and Ocean Surveillance Center (NCCOSC)
RDT&E Division
San Diego, CA 92152–5000

8. PERFORMING ORGANIZATION REPORT NUMBER

TD 2608

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Naval Research Laboratory Detachment
Code 435300
Stennis Space Center, Mississippi 39529–5000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

The High-Frequency Benchmark is a computer code being developed to employ a sophisticated ray tracing program coupled with a state-of-the-art ionospheric model chosen by the user. The merging of these two major components depends critically on the development of a spatial smoothing routine that accepts arbitrary ionospheric models as inputs. A significant improvement in the spatial interpolation has been made which enhances the flexibility of the model. The latest version of the Parameterized Ionospheric Model has been incorporated. This report describes these improvements and enhancements.

14. SUBJECT TERMS

Electromagnetic
Propagation
Atmosphere

15. NUMBER OF PAGES

19

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAME AS REPORT

21a. NAME OF RESPONSIBLE INDIVIDUAL	21b. TELEPHONE (Include Area Code)	21c. OFFICE SYMBOL
J. A. Ferguson	(619) 553–3062	Code 542

INITIAL DISTRIBUTION

Code 0012	Patent Counsel	(1)
Code 02712	Archive/Stock	(6)
Code 0274B	Library	(2)
Code 50	H. O. Porter	(1)
Code 54	J. H. Richter	(5)
Code 542	J. A. Ferguson	(10)
Code 542	D. B. Sailors	(20)
Code 542	W. K. Moision	(1)
Code 542	R. Rose	(1)
Code 542	R. A. Sprague	(20)
Code 772	J. A. Audia	(1)
Code 772	W. S. Bratt	(1)
Code 772	B. J. Satterlee	(1)
Code 833	G. Crane	(2)

Defense Technical Information Center
Alexandria, VA 22304–6145 (4)

NCCOSC Washington Liaison Office
Washington, DC 20363–5100

Center for Naval Analyses
Alexandria, VA 22302–0268

Navy Acquisition, Research and Development
Information Center (NARDIC)
Arlington, VA 22244–5114

GIDEP Operations Center
Corona, CA 91718–8000

NCCOSC Division Detachment
Warminster, PA 18974–5000

Chief of Naval Operations
Washington, DC 20350–2000

Naval Research Laboratory
Washington, DC 20375–5320

Naval Security Agency
Ft. Meade, MD 20755 (3)

Naval Security Group Command
Washington, DC 20393–5100 (3)

Naval Computer and Telecommunications
Command
Washington, DC 20390

Electromagnetic Compatibility Analysis Center
Annapolis, MD 21402–1187 (3)

Naval Postgraduate School
Monterey, CA 93943–5100

CECOM
Fort Monmouth, NJ 07703 (3)

U.S. Army Electronic Proving Ground
Fort Huachuca, AZ 85613–7110 (2)

Los Alamos National Laboratory
Los Alamos, NM 87545

National Telecommunications and
Information Administration
Annapolis, MD 21401

Institute for Telecommunication Sciences
Boulder, CO 80303–3328 (3)

Voice of America
Washington, DC 20003 (2)

Hunsucker Consulting
Fairbanks, AK 99709

Lucas Consulting
Boulder, CO 80301

Southwest Research Institute
San Antonio, TX 78284 (2)

SRI International
Arlington, VA 22209